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LOW FREQUENCY BREAKDOWN IN DIELECTRIC GASES

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Techniques Laboratory
Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York

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ABSTRACT

Experiments were conducted on the breakdown strength of several dielectric gases at 60 cycles per second in the region of a spark plug gap. Breakdown power of sulfur-hexafluoride (SF_6) was 20% greater when the electrodes were degassed at 50 microns compared to 1000 microns. As the concentration of SF_6 was decreased from 98% to 50%, only a small decrease in breakdown strength was noted. It is estimated that this factor can be used to reduce leakage of SF_6 by approximately 50%. The degradation effects of prolonged arcing were measured on breakdown onset voltage, extinguish voltage, and chemical decomposition. Gases analyzed, listed in their order of decreasing dielectric strength, include C_4F_8, Freon 115, SF_6, C_3F_8, Freon 116, and air. These experiments are to be continued and extended at microwave frequencies at S-band.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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INTRODUCTION

Dielectric gases have been used for a number of years in preventing electrical breakdown in high voltage equipment. The primary mechanism at work in these gases is its ability to capture electrons before they can acquire the energy required to produce further ionization. The most popular dielectric gas is sulfur-hexafluoride although consideration is presently being given to other gases in an effort to reduce the cost or increase the capability of devices using such gases. Other areas under consideration involve the dilution of these dielectric gases with air in order to reduce cost. The degree to which the electrode surfaces are desorbed of air prior to filling the device with a dielectric gas is also believed to have an effect on the breakdown strength.

The object of this program is to experimentally evaluate the effects that evacuation and dilution have on the breakdown strength of a number of different dielectric gases including sulfur-hexafluoride. It is anticipated that this data will lead to more efficient and economical use of dielectric gases, especially as it pertains to microwave equipment.

The experiments were carried out with 60-cycle a-c voltages applied across a spark plug gap filled with the dielectric gas mixture. The evaluations performed through these simple and rapid procedures have indicated whether such gases are worthwhile for future investigation in microwave components. The effects which evacuation and mixing have on breakdown at a-c power frequencies are positively correlated with breakdown at microwave frequencies.[1]

It must be kept in mind that the electric fields dealt with here are nonlinear and for this reason field strength improvements for various gases are not apt to be the same as for uniform fields of two closely spaced hemispheres.

PROCEDURE

The electrical setup is illustrated in Figure 1. A variac was used to manually increase the voltage across the 10 kv transformer until the gas sample broke down across the spark plug. The electrodes of the spark plug were sealed off to a confined volume where the gas sample was present. Upon breakdown a voltage was sensed by a Hughes 104E Memo-Scope (Figure 2) at J1 which in turn gave a visual plot of the breakdown pattern. The 1 megohm resistor was used for current limiting. S1 in conjunction with R1, R2, and R3 provided metering of voltages to full scales of 2.5 kv, 5 kv and 10 kv on the voltmeter V. Full scale deflection required 1 milliampere, only 3% of the full current rating of the transformer.

Figure 3 is a diagram of the gaseous equipment. By proper manipulation of the valves the confined space about the electrodes of the spark plug can be evacuated down to any pressure above 15 microns Hg which is the limit of the pump. The space can then be back-filled with any gas or mixture of gases for evaluation. Since the test space is confined by glass designed for vacuum use the evaluations were not attempted for pressures above one atmosphere. Copper tubing was used between the valve sealing off the lecture bottle and those sealing off the regulators. Here it was necessary to use higher pressures for the

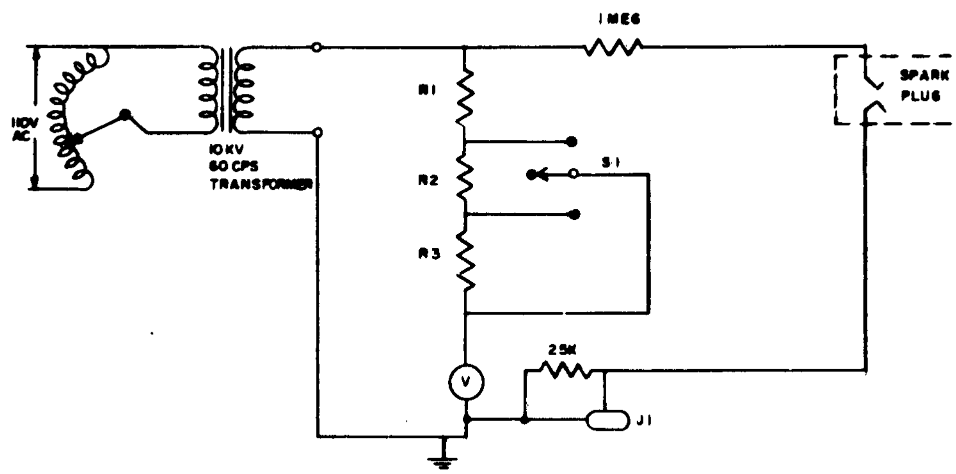


Figure 1. Electrical Setup

Figure 2. Hughes 104E Memo-Scope

purpose of mixing different gases and also holding the mixed gas sample for a series of measurements. Immediately prior to mixing up a sample the lecture bottle with its associated hardware was evacuated to less than one millimeter Hg. The mixture was then made by valving off the vacuum system and backfilling by setting and opening the regulators for particular pressures. Once the mixture was completed the test space (that space which is bounded by the glass tubing between the spark plug and the closest valve) could be backfilled to the desired pressure. Metering was provided for pressures ranging from one atmosphere down to one micron Hg.

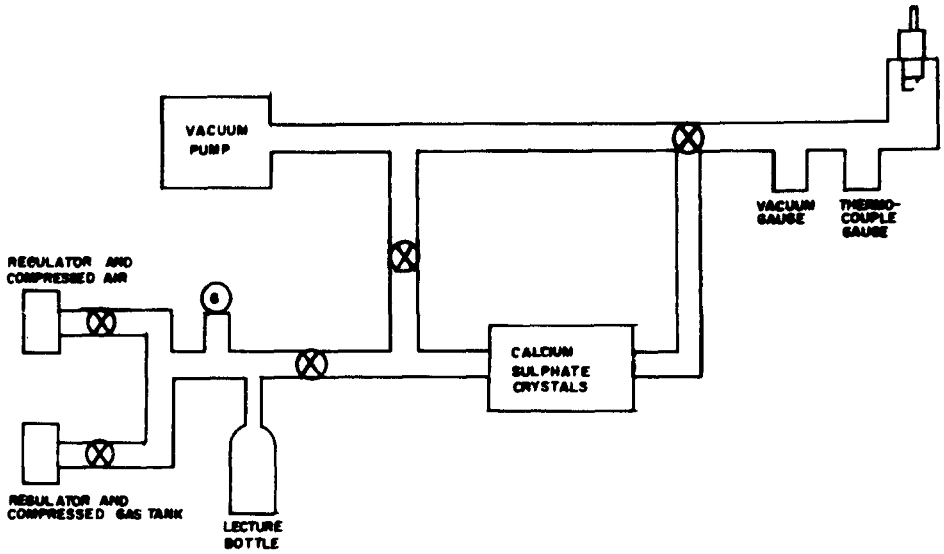


Figure 3. Gaseous Equipment

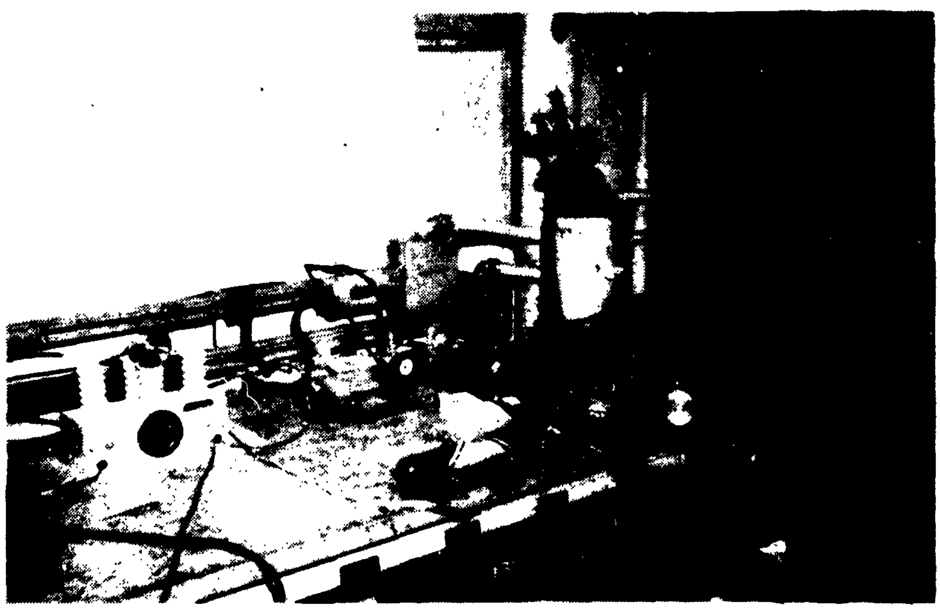


Figure 4. Gaseous Apparatus

EXPERIMENTAL DATA

All the measurements were made with a small sample of radioactive material taped to the outside surface of the glass tube adjacent to the spark plug. Although the sample was one which is used to calibrate a Geiger counter the radiation it provided was sufficient to produce a noticeable reduction in the statistical time lag required for breakdown. Figure 5 shows two breakdown curves for air. These curves compare the difference of breakdown voltages with and without a radiation source taped to the glass tube. Statistical time lags

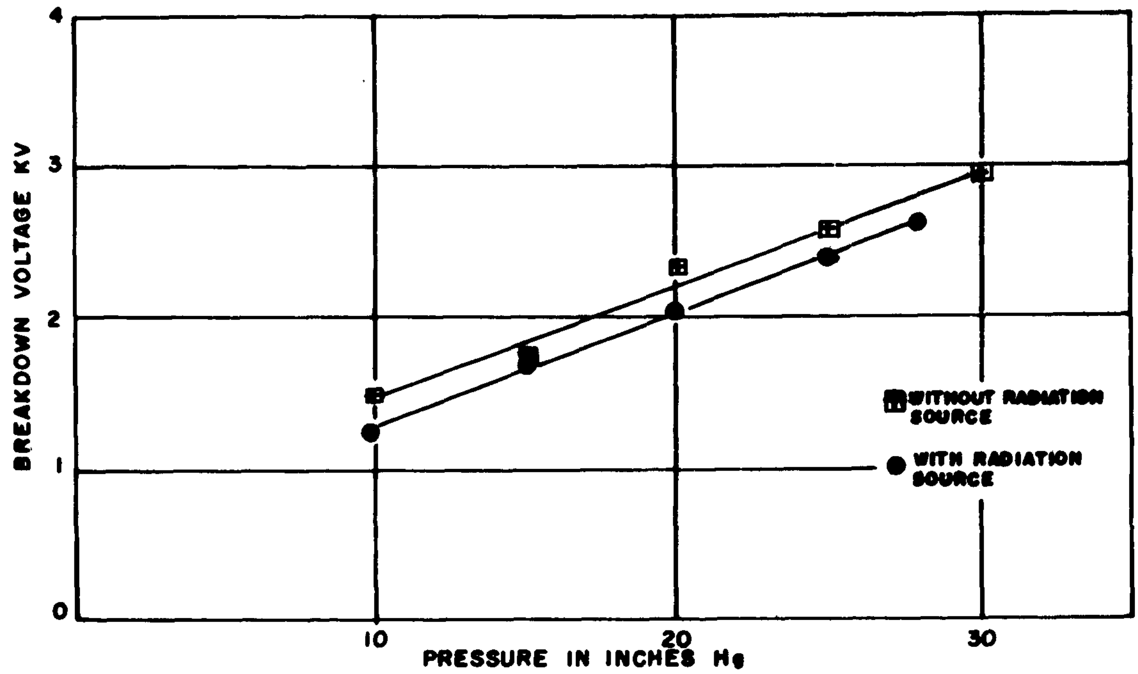


Figure 5. Breakdown Voltage With and Without Radiation Source versus Pressure

were made to occur within a few seconds.

The normalized voltage ratio R(which hereafter shall be defined as the ratio of the breakdown voltage of a dielectric gas or mixture thereof to that of air) is given in Table 1 for 28 inches Hg of SF_6 applied to the electrodes as described. The data for this table was taken later during the experiment at which time the breakdown voltage of air had increased to 2.9 kv for 28 inches Hg absolute. This represented an increase of about 10% over that shown in Figure 5.

Figure 6 shows the effect that pressure and percentage of mixture have on the breakdown strength of SF_6. The data shown in this figure was taken in the order of 0%, 95% down to 5% inclusive, and finally 100% of sulfur hexafluoride. Air was used as the other constituent in producing the mixture.

Figure 7 is a plot of the square of the normalized voltage ratio (R^2) versus the percentage of SF_6 mixed in air. This curve was plotted to indicate power-handling capability. From Figure 6 it can be seen that the breakdown strength (or R) at first rises rapidly for small percentages of SF_6 added to the air but levels off as the mixture approaches 100% SF_6. The effect of squaring this ratio in breakdown strengths (R^2) tends to establish a

more proportionate relationship between percentage of mixture of SF_6 and power ratio.

TABLE I

SF_6 to Air Voltage Ratio for Spark Plug Electrodes

Conditions of Electrode to which 28 inches of SF_6 is applied	Breakdown Voltage KV	SF_6 to Air Ratio Voltage	Ratio Voltage Square
Evacuated to 1000 microns of air	5.2	1.8	3.2
Evacuated to 50 microns of air	5.5	1.9	3.6
Evacuated to 40 microns of air, purged with 28 inches of SF_6, sputtered with an arc for one minute, and evacuated to 40 microns	5.70 5.75	1.96 1.98	3.85 3.9

NOTE:
The breakdown voltage of 28 inches of air at this stage of the experiments was measured at 2.9 kilovolts.

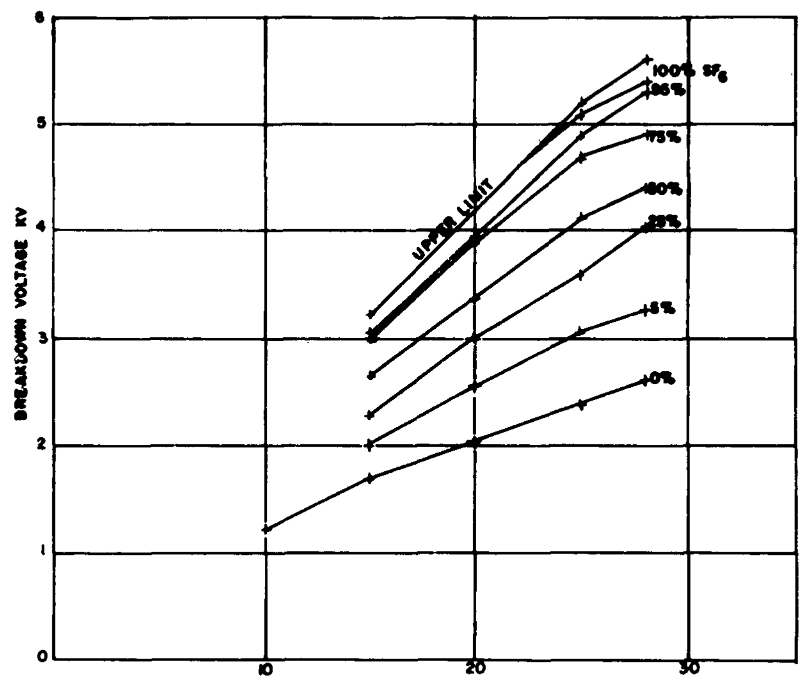


Figure 6. Breakdown Voltage of Mixtures of SF_6 and Air versus Pressure Abs

A gas which does maintain its breakdown strength characteristics over a wide range of percentage mixture is Freon 116 (Figure 8). Unfortunately, it appears that this gas by itself does not exhibit a very high voltage breakdown ratio R, in which case its further

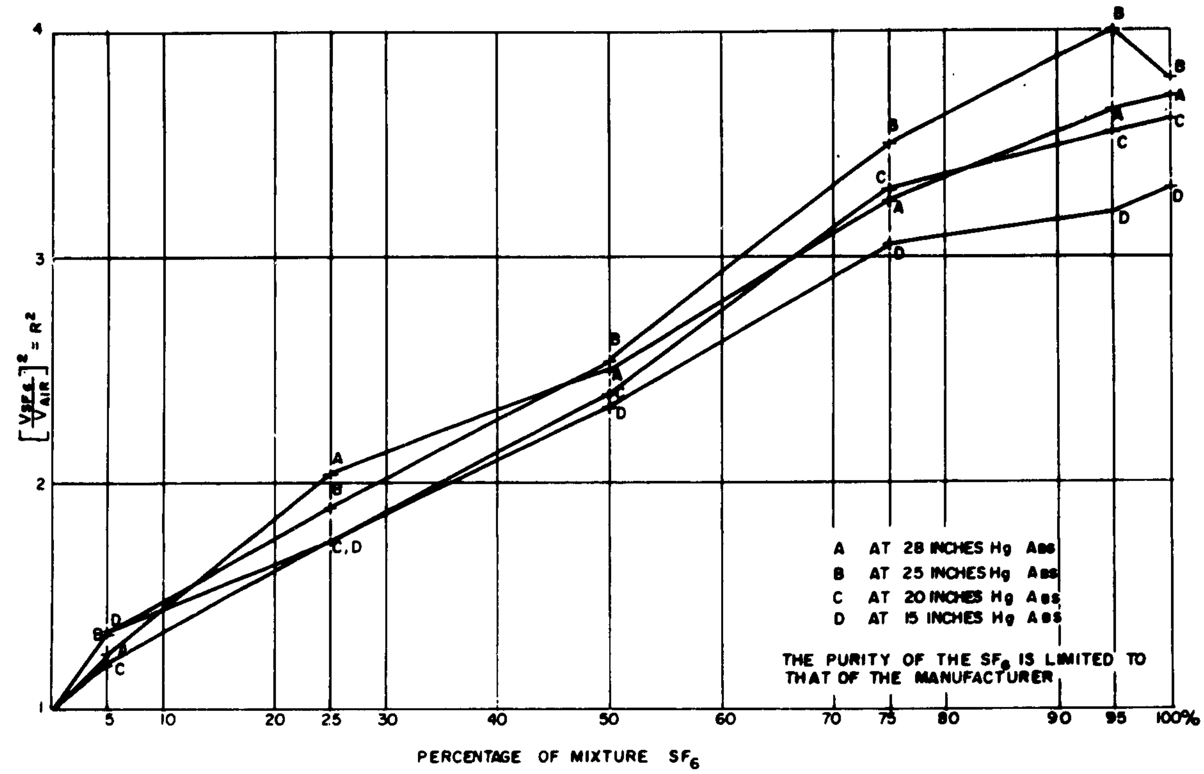


Figure 7. Square of Ratio of Breakdown Voltage of SF_6 to Air versus Percent of SF_6

consideration will have to await tests under conditions of different frequencies and geometrical configurations.

The breakdown voltages of the dielectric gases that were evaluated are shown in Figures 9 and 10. The family of curves in Figure 9 represents the gases as received from the manufacturer. This verifies some of the results reported by others.[1,2] Figure 10 represents mixtures of 50% of the dielectric gas and 50% air.

With many of the gas samples it was found that the voltage for the very first arc was about 10% greater than the voltages for subsequent arcs. These subsequent arcs were measured within minutes of the first but it was difficult to observe any trend toward recovery of the gas sample to the state at which the initial arc was measured. However, this difference between the first arc and the subsequent arcs was not observed to be greater than 10%. The breakdown voltages of first arcs are shown in Figures 11 and 12.

The breakdown voltage for each dielectric gas was measured for at least two values of concentration, 100%, and for mixtures of 50% of the gas and 50% air. The gas sample was backfilled into a confined volume in which the voltage across the spark plug gap was increased until an arc was detected. Each measurement was rechecked at least three times. After recording the onset voltage for breakdown the voltage was set to produce a steady arc across the gap lasting about one minute. The voltage was then slowly reduced until

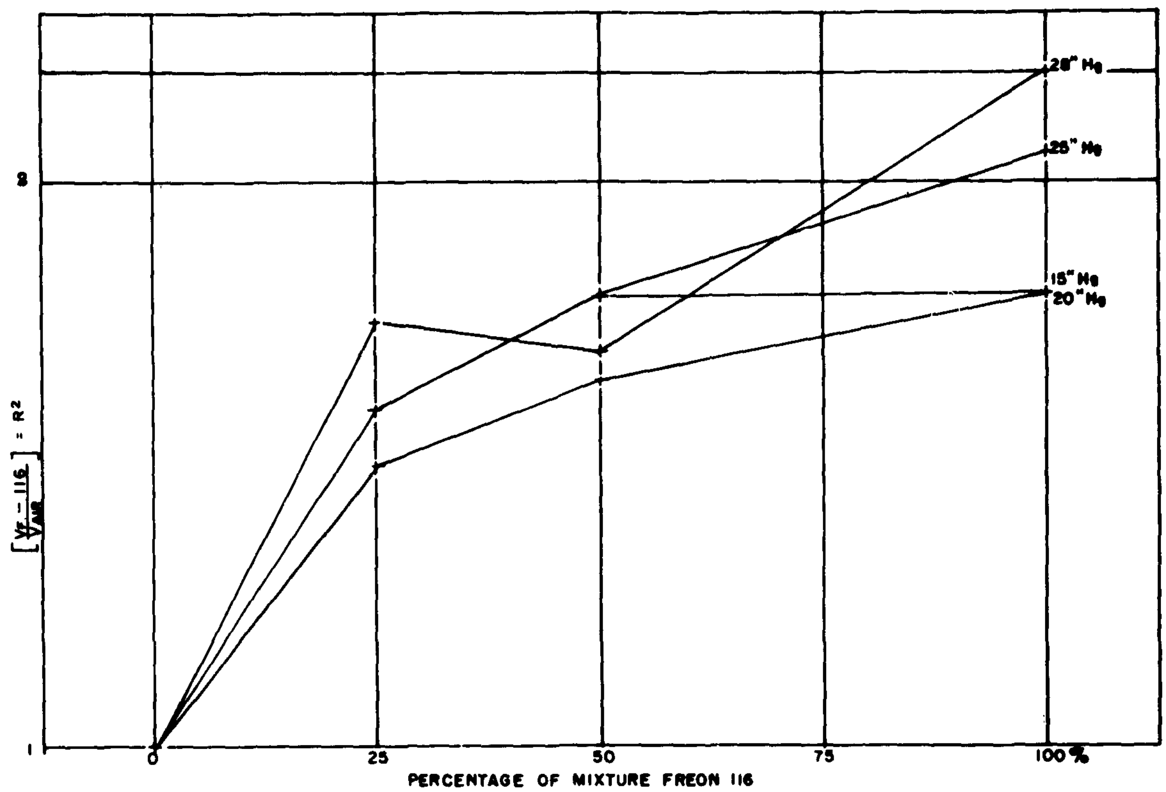


Figure 8. Square of Ratio of Breakdown Voltage of Freon 116 to Air versus Percent of Freon 116

the arc was extinguished at which point the voltage was again recorded. Onset voltage for breakdown was again recorded and rechecked for this same gas sample which had now undergone one minute continuous arcing. These voltages are shown in Figures 13 and 14. The process was repeated for some of the samples to verify that the nature of the gas and not random surface conditions was the dominating factor in breakdown.

Pressures remaining in the confined volume after one minute of arcing are shown in Table II. Increases in pressure are apparently due to decomposition of the gas during arcing from which more gas molecules result. The pressure increase could not have been due to a temperature rise. This was noted when no drop in pressure could be observed after the arc was extinguished and the gas volume, confined only by the thin glass tubing, was allowed to set at room temperature for several minutes. This increase in pressure therefore must have been due to the fact that the arc decomposed the dielectric gas chemically whereupon a greater number of lighter gas molecules resulted.

The bottle pressure of each gas was measured. It turned out that the bottle pressures of SF_6 and Freon 116 were about 400 psig and 500 psig respectively. The bottle pressures of C_3F_8 and Freon 115 were about 130 psig. C_4F_8, however, turned out to be only 28 psig. Since its pressure quickly recovered to this value after it was lowered by valving some of

TABLE II

Remaining Pressure After 1 Minute of Continuous Arcing

Gas in Confined Volume	Initial Pressure Inches Hg Abs				Remarks
	28	25	20	15	
SF_6	28	25	20	15	No noticeable change
50% SF_6 50% Air	28	25	20	15	No noticeable change
C_4F_8	Approx 10% Higher				Pressure not recorded but recalled from memory
50% C_4F_8 50% Air	Approx 10% Higher				Pressure not recorded but recalled from memory
C_3F_8	29+	26.25	21.0	15.5	
50% C_3F_8 50% Air	29+	26	20.75	15.25	
Freon 116	28.75	25.5	20.25	15+	
50% Freon 116 50% Air	28.75	25.5	20.25	15.2	
Freon 115	29	25.85	20.75	15.5	
50% Freon 115 50% Air	29+	26.0	20.5	15.25	

the gas out of the bottle, it can be concluded that the vapor pressure of C_4F_8 at room temperature is 28 psig. This would certainly pose limitations on its use as far as pressurization is concerned.

It appeared that carbon deposits resulted when C_3F_8, C_4F_8, Freon 116, and Freon 115 were subjected to continuous arcing. No noticeable deposits were cited with SF_6.

Figure 15 is a photograph of the region adjacent to the spark plug as it appeared after all the tests were run. The deposits of carbon that were produced sometime while C_3F_8, C_4F_8, Freon 116, and Freon 115 were undergoing sustained arcing can be seen through the glass tubing.

CONCLUSIONS

A definite increase in over-all breakdown strength occurs when SF_6 is applied to the electrodes after they have been evacuated, purged with the dielectric gas, and then evacuated again. As illustrated in Table I this procedure results in a normalized voltage ratio R (the ratio of the breakdown voltage of a dielectric gas to that of air) which is 10% greater than that for SF_6 applied after only one evacuation. Its effect on power-handling capability represents a 21% increase (R^2) over that for SF_6 applied after only one evacuation.

Whenever the electrodes were subjected to air or a mixture of air and a dielectric gas the electrodes had to be evacuated, purged, discharged, and evacuated again in order to realize the best strength of a pure sample of dielectric gas. It seems as though the

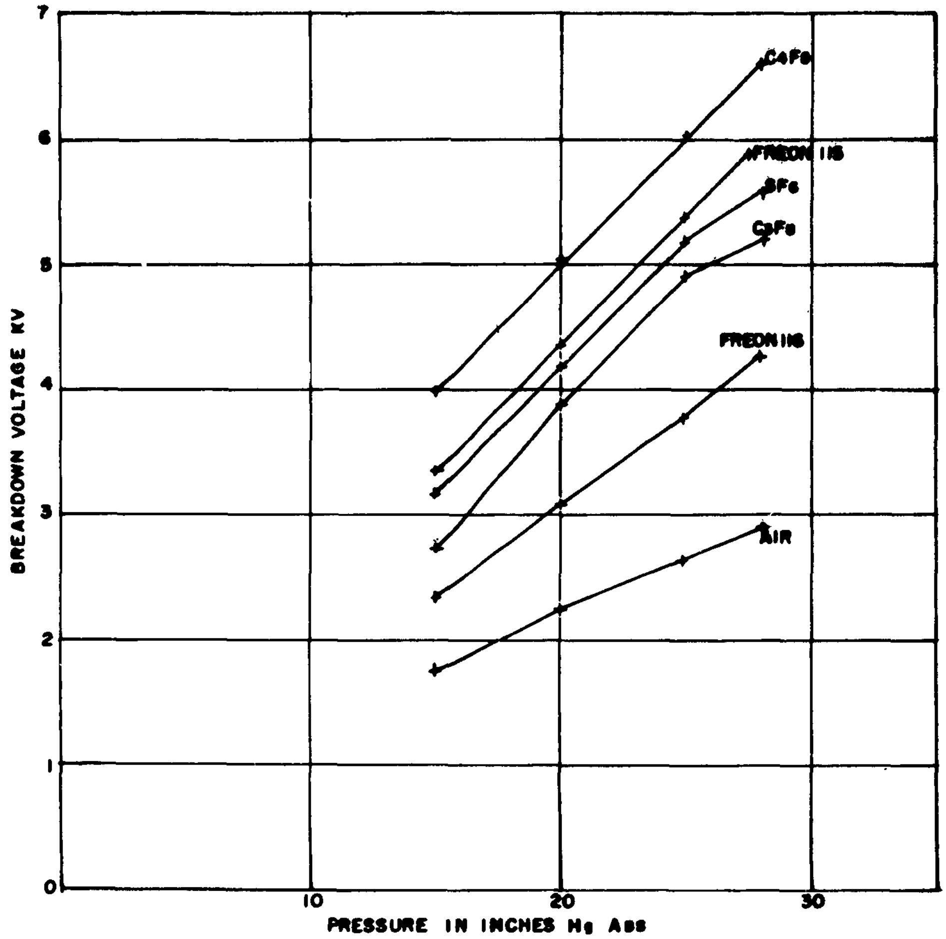


Figure 9. Breakdown Voltage of Dielectric Gases versus Pressure in Inches Hg Abs Sparkplug Gap

electrode has an affinity for absorbing air molecules, thereby causing a slight degradation in breakdown strength.

After this initial drop in voltage breakdown strength, R decreases at a slower rate with respect to percentage of air mixed with the dielectric gas. R begins to decrease sharply only when the percentage of dielectric gas becomes less than approximately 25% (Figure 6). Although the breakdown voltage in this respect is nonlinear the power-handling capability is more proportional with percentage of mixture as illustrated by plotting the square of R (Figure 7). The only exception to this is Freon 116. The breakdown strength of this gas behaved so nonlinearly that this nonlinear effect was still observed in the graph of power-handling capability (the square of R) (Figure 8). Unfortunately the breakdown strength of Freon 116 does not appear very promising. However, it will be briefly checked at microwave frequencies and for other electrode configurations.[2]

With reservations, C_4F_8 and Freon 115 are superior to SF_6. For each of these gases (when not mixed with air) R^2 was found to be approximately 5.2, 4.2 and 3.9 respectively. Due to chemical decomposition from which carbon is a by-product a high safety factor must

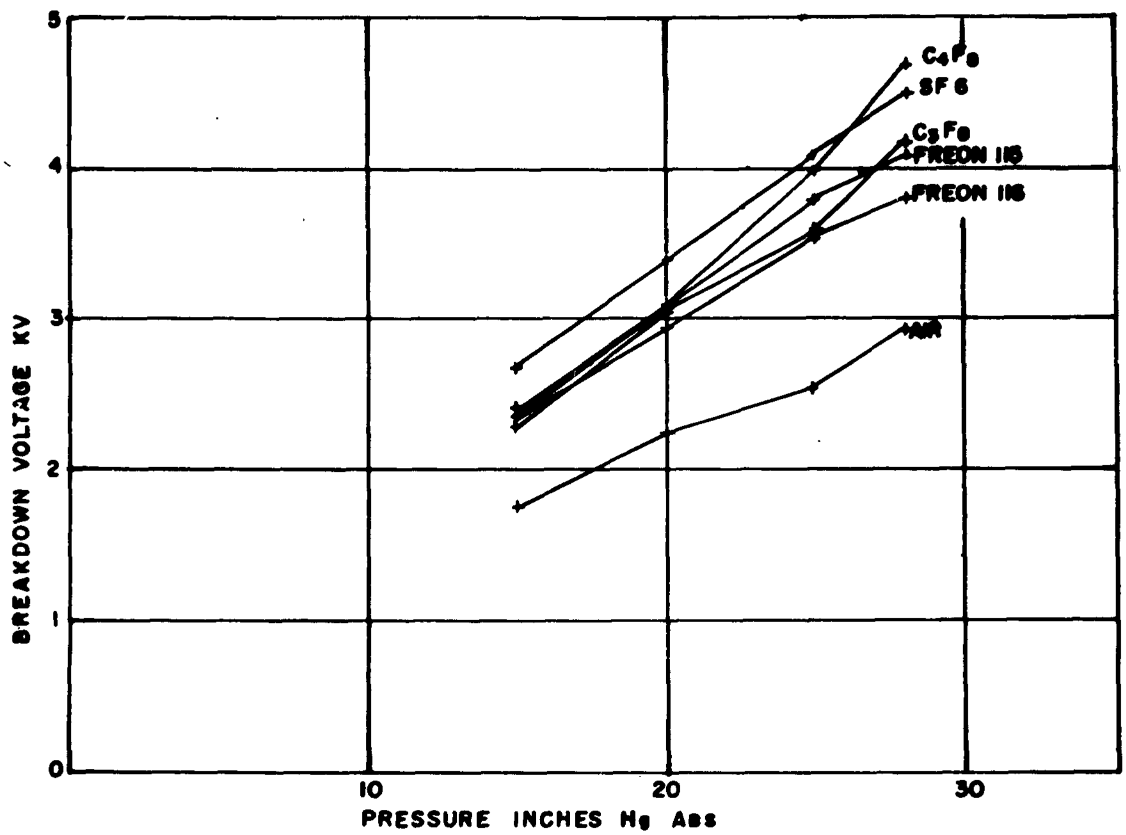


Figure 10. Breakdown Voltage of Mixture of 50% Dielectric Gas +50% Air versus Pressure in Inches Hg Abs

be used with C_4F_8 and Freon 115 to assure that absolutely no arcing occurs.

Under continuous arcing C_4F_8, C_3F_8, Freon 116 and Freon 115 underwent chemical decomposition resulting in a great number of lighter gas molecules. Carbon was also deposited under these conditions. The effect that arcing had on the field strength of these gases was a degradation of the onset of breakdown and a degradation of the extinguish voltage.

SF_6 is most practical for mixing with air in order to reduce over-all costs. It still appears to have the best over-all characteristics for use in high power equipment.

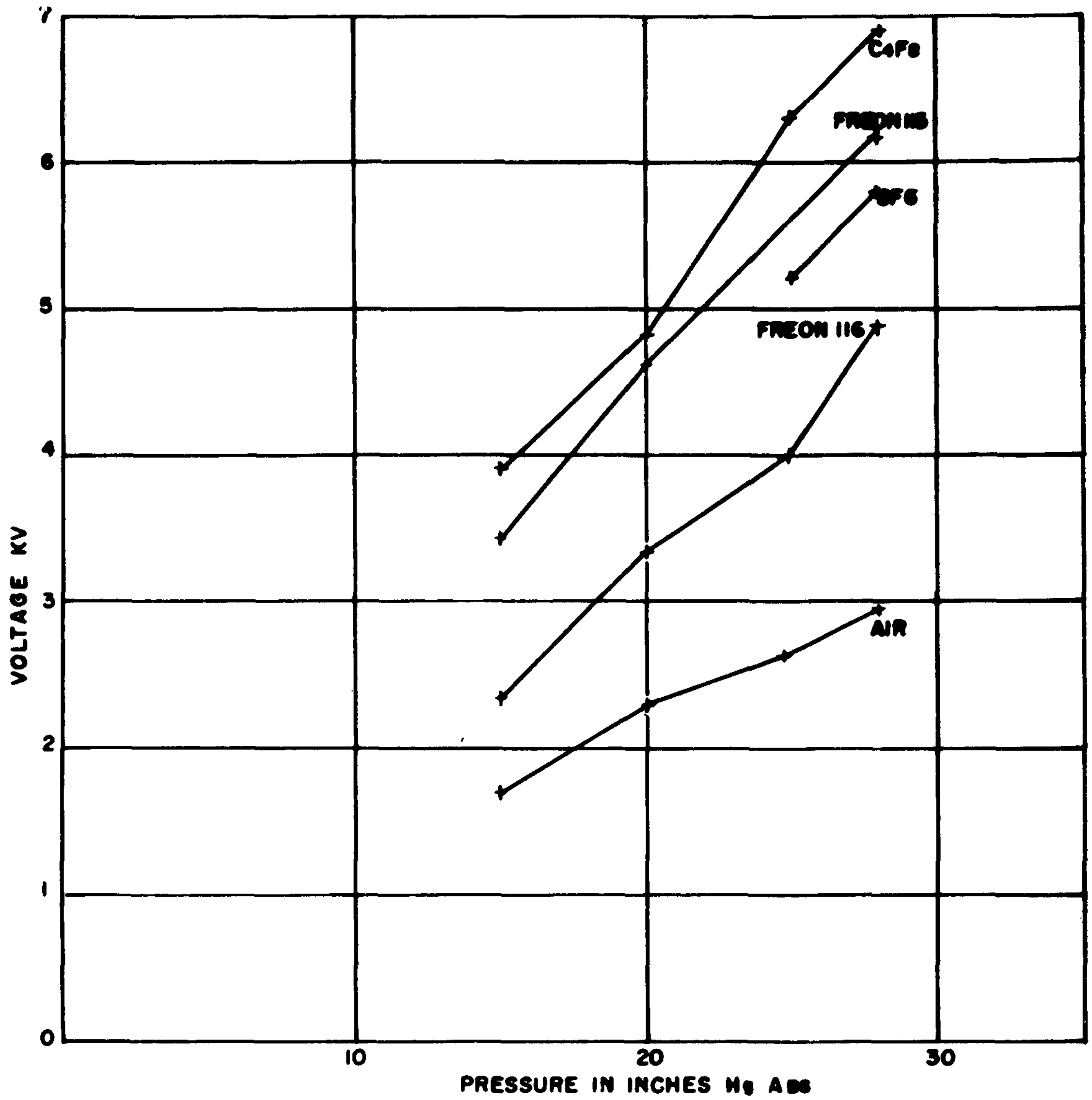


Figure 11. First Arc for 100% Mixture of Dielectric Gas versus Pressure in Inches Hg Abs

RECOMMENDATIONS

When using C_4F_8 and Freon 115 a substantial safety factor must be introduced in order to prevent the occurrence of even a single arc. Maximum pressurization is limited to the vapor pressure of C_4F_8 which is approximately 26 psig at room temperature.

SF_6, or mixtures of air and SF_6, should be used in systems where intermittent arcing is possible. The gas should be kept as dry[4] as possible.

Freon 116 and C_3F_8 were found to have breakdown strengths inferior to that of SF_6 insofar as the test conditions described here are concerned. Freon 116 and C_3F_8 should not be completely eliminated from further investigations. The properties under conditions of different frequencies, pressure and field configurations may change considerably.[2]

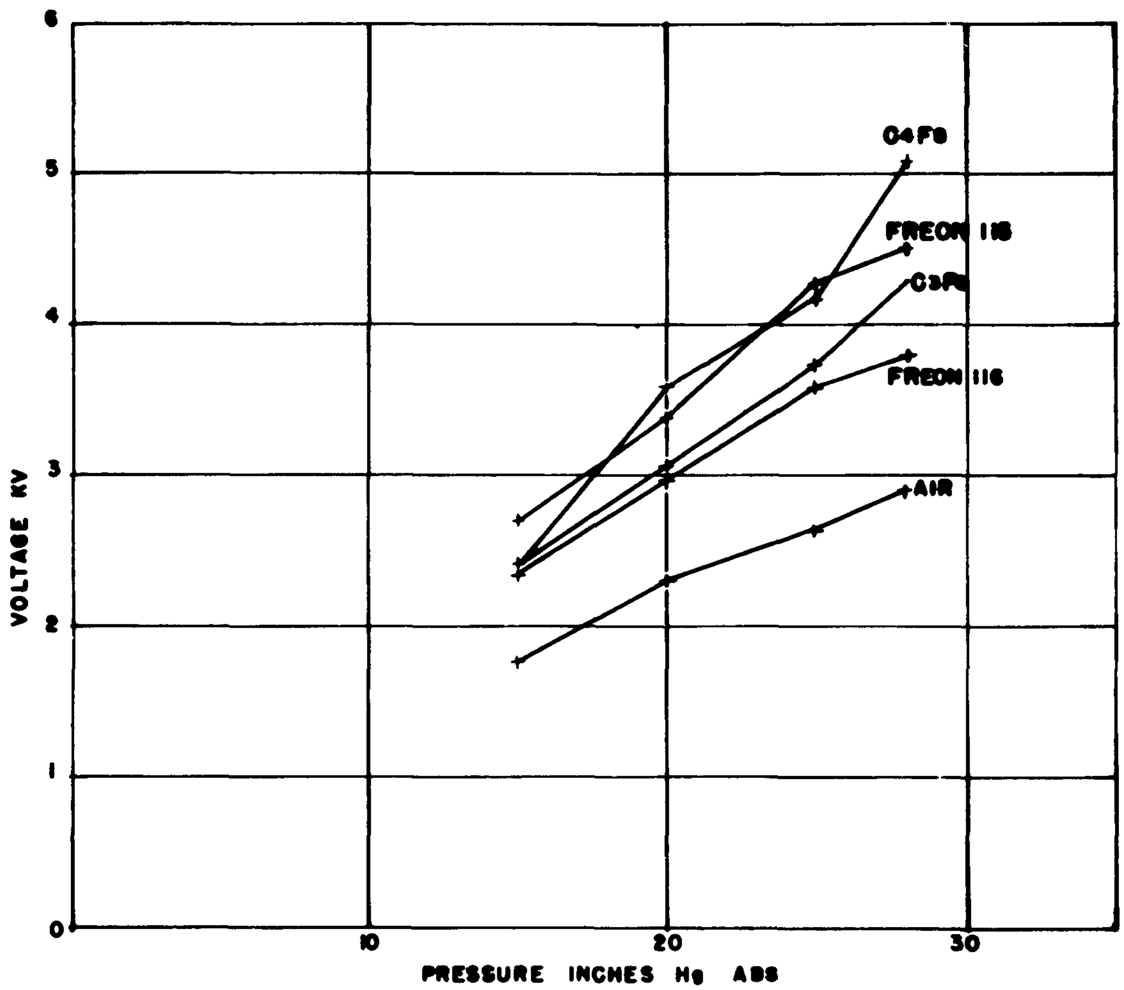


Figure 12. First Arc for 50% Mixture of Dielectric Gas with Air versus Pressure in Inches Hg Abs

It is recommended that SF_6 be mixed with air as a means of reducing leakage costs. A current problem existing with microwave systems in the field concerns leakage of the relatively expensive dielectric gas. Recent attempts to improve seals, gaskets, moving joints, and other regions where the dielectric gas might be escaping have not eliminated the problem completely. The use of gas mixtures containing certain percentages of SF_6 and dry air can lead to significant reductions in leakage costs.

For example, suppose it is required to operate an S-band microwave system at 50 megawatts of peak power. When filled with one atmosphere of air this same system undergoes electrical breakdown at .5 megawatts. It is therefore necessary to increase the power-handling capability by a factor of 100. The system also contains a gas leak.

The example is based on the following assumptions:

The power ratio of SF_6 and air mixtures varies directly as the percentage of SF_6. (See

conclusions.)

. The breakdown power increases with the square of the pressure. This assumption is quite general.[3]

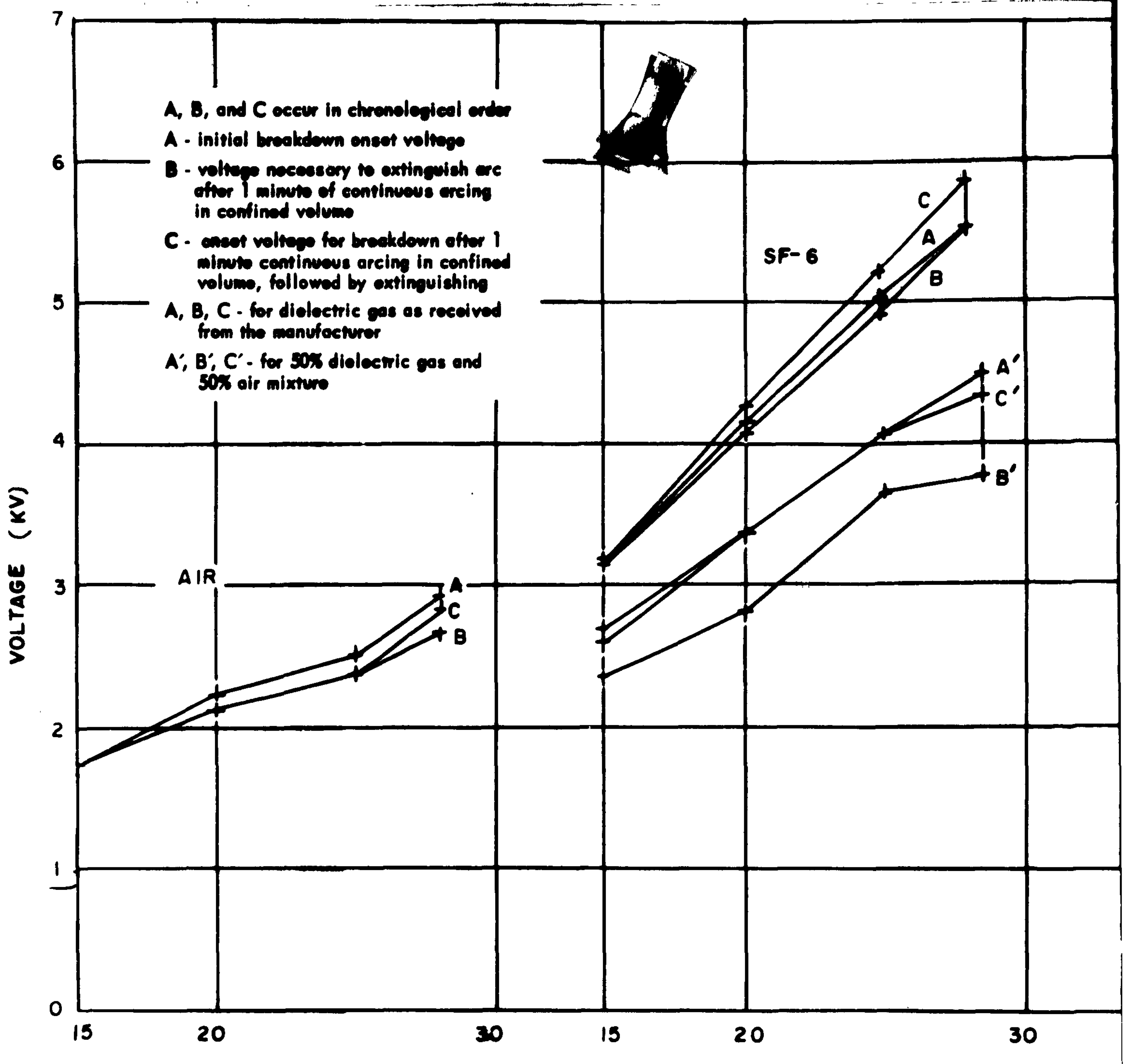
. The size of the leak (opening) remains constant.

. The power ratio of SF_6 in this system is equal to 10.

The following set of operating parameters is presented:

1. Percentage of SF_6 in mixture Percentage of air	0% 100%	5% 95%	25% 75%	50% 50%	75% 25%	100% 0%
2. Power ratio (R^2) of mixture	1	1.45	3.25	5.5	7.75	10
3. Necessary pressure in atmospheres absolute	10	8.3	5.5	4.25	3.6	3.16
In atmospheres gauge	9	7.3	4.5	3.25	2.6	2.16
4. Leakage rate of mixture, (Normalized to last column)	4.16	3.37	2.08	1.50	1.20	1.00
5. Leakage rate of SF_6, line 1 times line 4 (Normalized to last column)	0	.17	.52	.75	.90	1.00

Block 5 gives the relative amount of SF_6 that would be lost to leakage. Therefore, if one is able and willing to use a 25% mixture at 5.5 atmospheres absolute the leakage rate of SF_6 will be reduced to 52% compared to using a 100% mixture at 3.16 atmospheres; or one may choose to use a 50% mixture, pressurize at 4.25 atmospheres absolute and realize a 75% SF_6 leakage rate. If one could pressurize up to 3.6 atmospheres a 90% leakage rate would be obtained. In any case it is not recommended that pressurization be brought above 6 atmospheres.


A, B, and C occur in chronological order
A - initial breakdown onset voltage
B - voltage necessary to extinguish arc after 1 minute of continuous arcing in confined volume
C - onset voltage for breakdown after 1 minute continuous arcing in confined volume, followed by extinguishing
A, B, C - for dielectric gas as received from the manufacturer
A', B', C' - for 50% dielectric gas and 50% air mixture
VOLTAGE (KV)
AIR
SF-6
A
B
C
A'
B'
C'
0
1
2
3
4
5
6
7
15
20
30
15
20
30

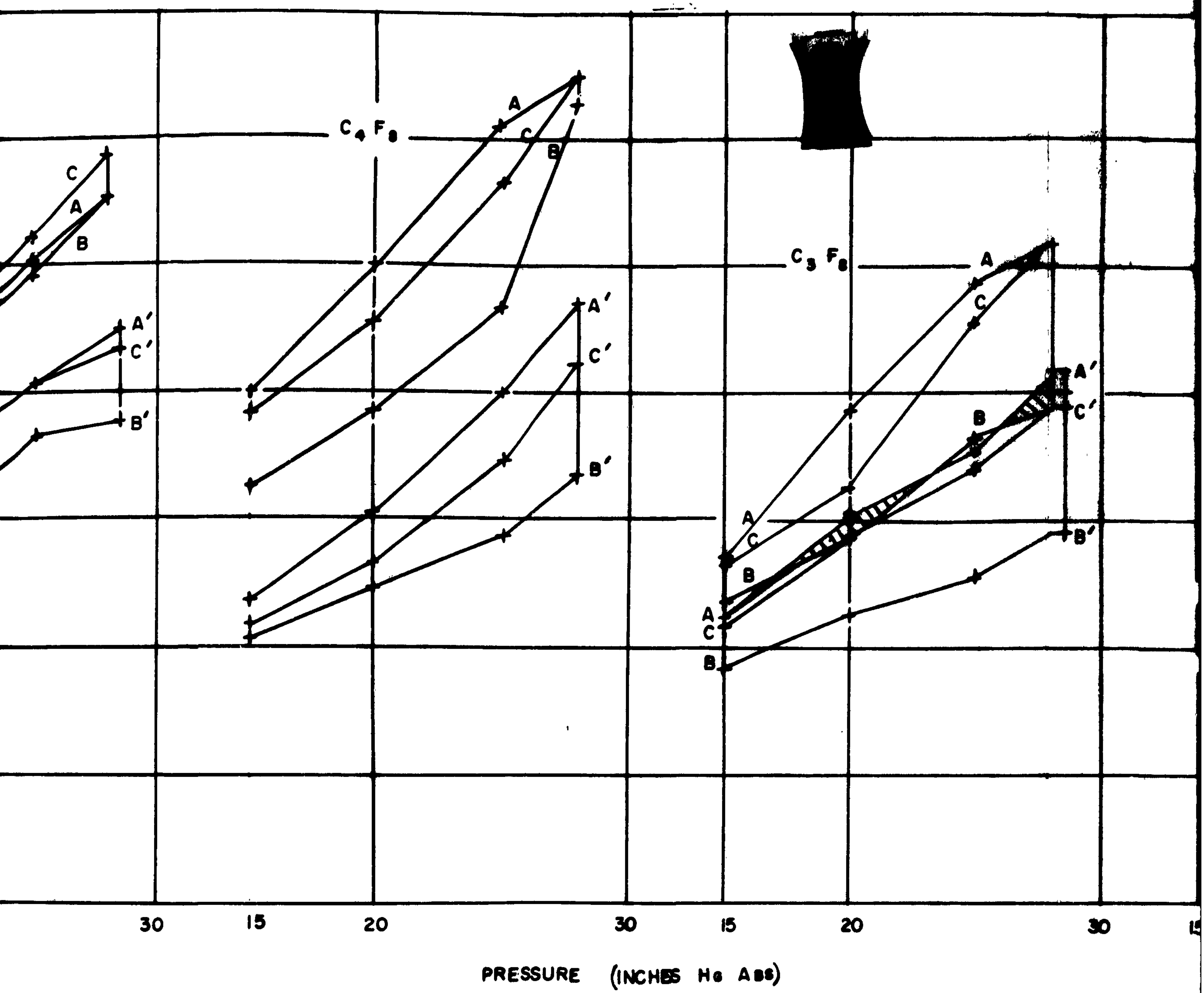
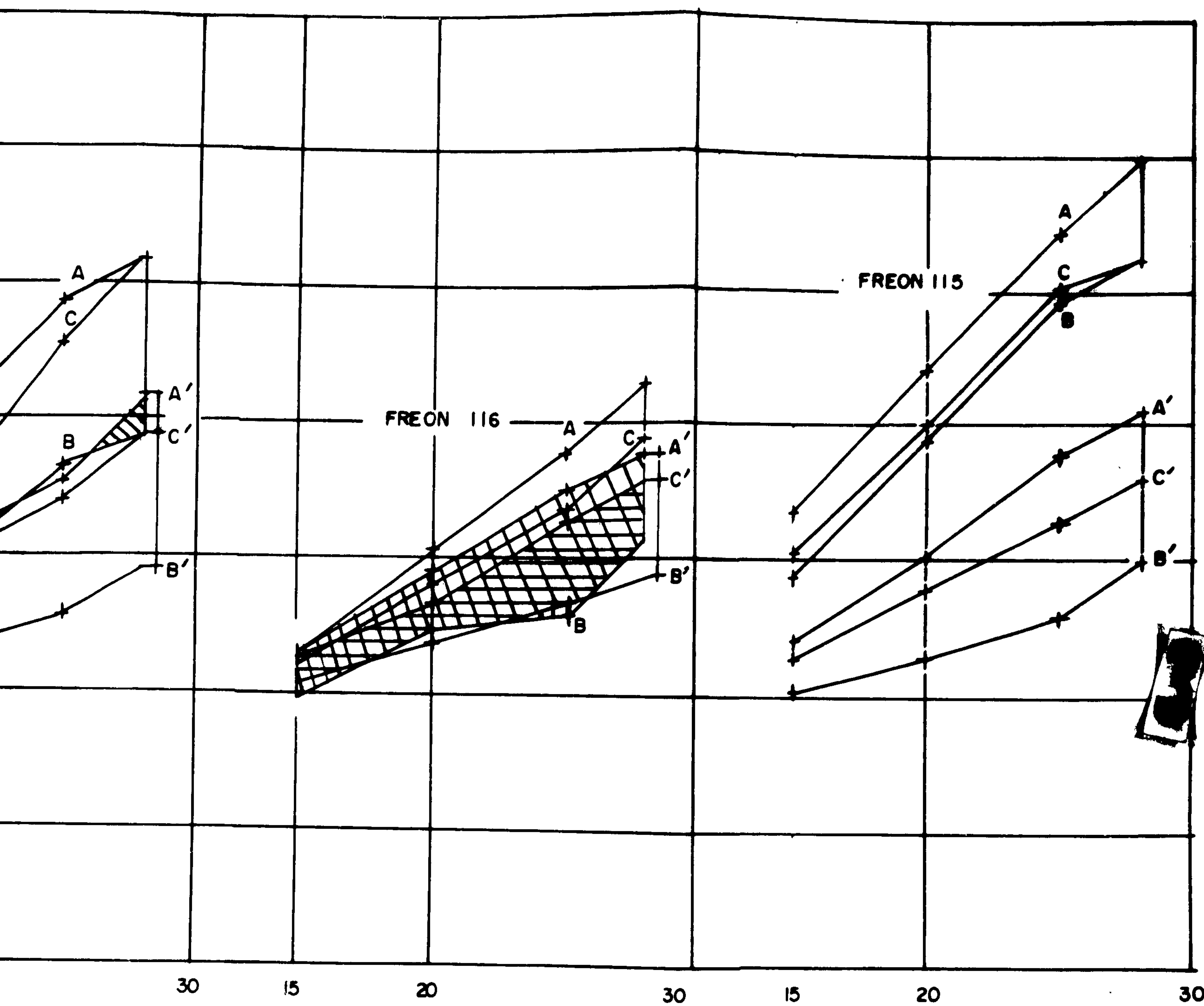


Figure 13. Breakdown Voltage, Extinguish Voltage versus Pressure



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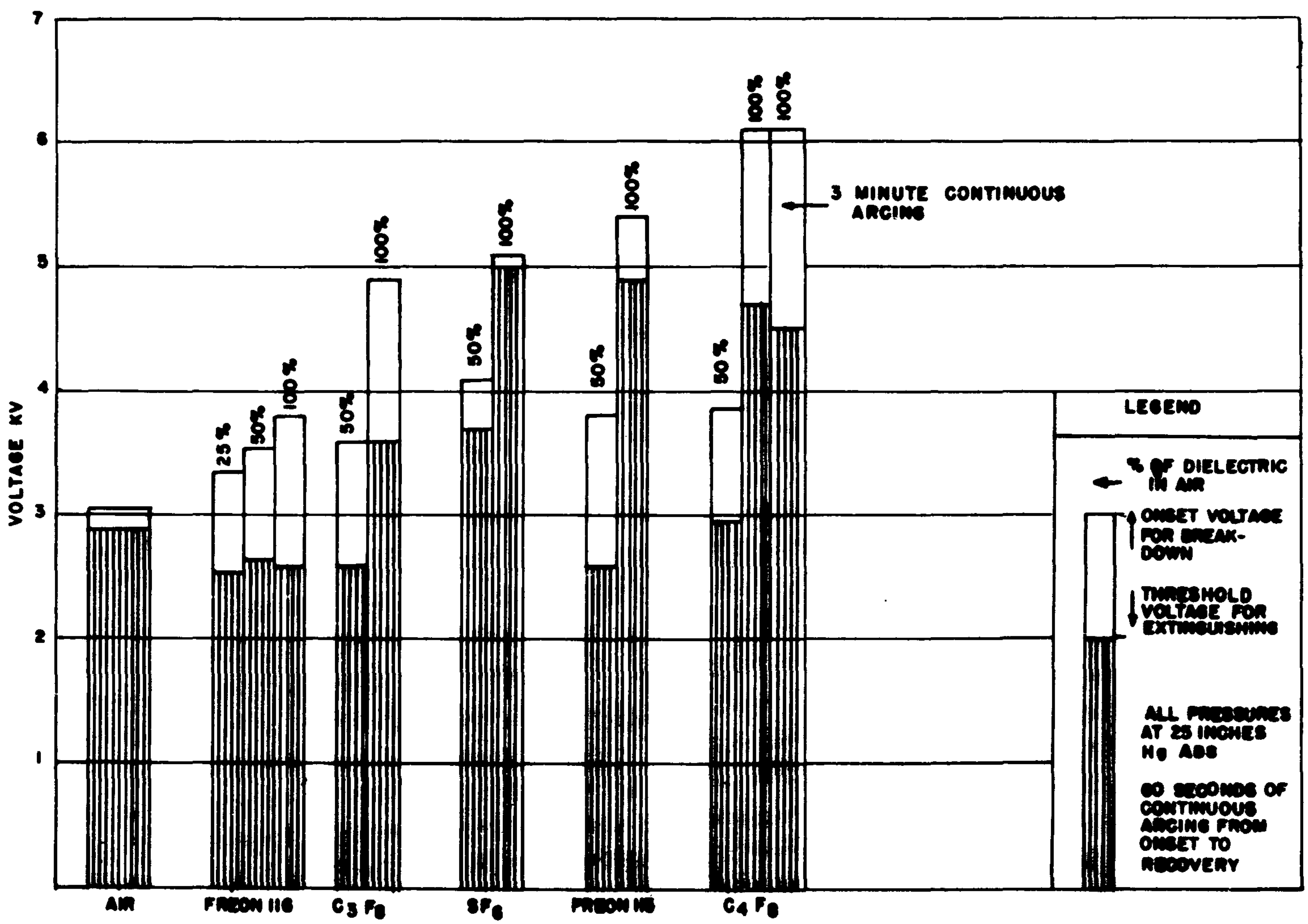

Figure 14. Onset and Extinguish Voltages for Different Gas Samples.

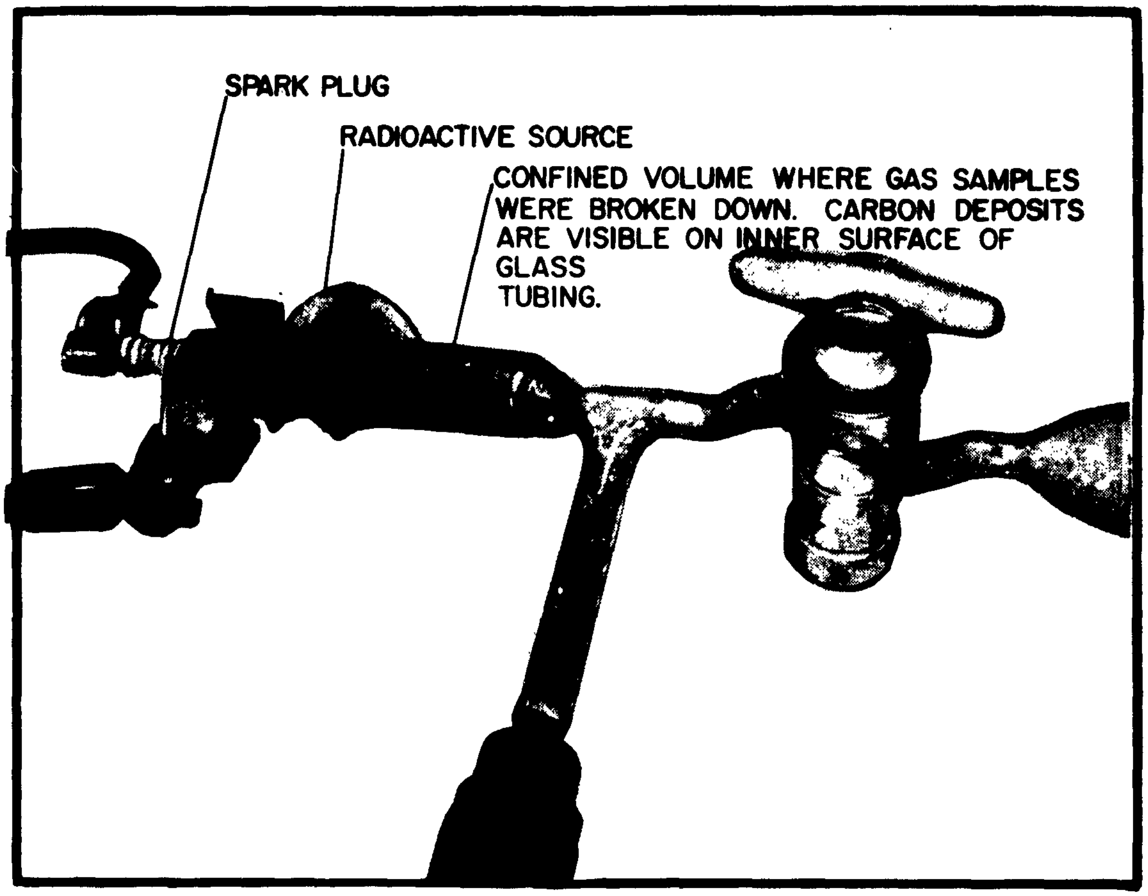

Figure 15. Photograph Showing Carbon Deposits Due to Chemical Decomposition.

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2. Electric Arcs

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1. Dielectrics
2. Electric Arcs

I. Project No. 4506, Task No. 450602
II. Vannicola, V.C.
III. In ASTIA collection

Rome Air Development Center, Griffiss AF Base, N.Y. Rpt No. RADC-TDR-62-585. LOW FREQUENCY BREAKDOWN IN DIELECTRIC GASES. Dec 62, 19p. incl illus., tables.

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